The implications of the new Z=0 stellar models and yields on the early metal pollution of the intergalactic medium

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ABSTRACT

Motivated by the recent detection of metals in different components of the high redshift universe and by the abundance ratios measured in the extremely metal-poor stars of our Galaxy, we study the nucleosynthesis constraints that this imposes on an early generation of stars (Population III). To do so we take into account the chemical yields obtained from homogeneous evolutionary calculations of zero metal stars in the mass range $3 \lesssim m/M_{\odot} \lesssim 40$ (Limongi et al. 2000, Chieffi et al. 2001). We also consider the role played by metal-free very massive objects (m> 100 $M_{\odot}$). Using both analytical and numerical chemical evolution models, we confront model predictions from the different choices of the mass function proposed for Population III with the observational constraints. We show that low values of star formation efficiency (< 1%) are required so as not to exceed the minimum metallicity ([C/H]≈ -2.4) measured in the high redshift systems for any of the IMFs proposed. We also show that the observational constraints require $\Omega_{sr} < 3 \times 10^{-3}\Omega_b$, confirming previous claims that the possible contribution of the stellar remnants from Population III to the baryonic dark matter is insignificant. At present, however, the scarcity of abundance measurements for high redshift systems does not permit us to put severe limitations on the nature of the initial mass function for Population III. In fact, overabundances of alpha-elements with respect to iron of the order of those measured in damped Lyman-α systems are obtained for any of the IMFs tested. Nevertheless, to account for the very large [C,N/Fe] ratios found in a considerable number of extremely metal-poor stars of our Galaxy, an IMF peaking at the intermediate stellar mass range ($4 - 8$ $M_{\odot}$) is needed.

Subject headings: galaxies: abundances — galaxies: intergalactic medium —

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1. Introduction

In current cold dark matter (CDM) hierarchic cosmological models, shortly after the Big Bang (redshifts $z \sim 10-30$) the primordial gas cooled rapidly and fragmented. From the first structures, with typical masses between 10^5 and 10^8 $M_\odot$, it is believed that a very early generation of stars, Population III, formed. Since the chemical content of these first structures was primordial (H, ^{4}He and traces of D, ^{3}He and ^{7}Li), this first generation of stars must have been formed essentially free of metals ($Z \sim 10^{-9}$).

The possible existence of Population III was originally postulated because of the presence of metal overabundances in Population II stars and especially due to the so-called G-dwarf problem: the discrepancy between the number of observed low mass metal-poor stars and that predicted by simple (closed) models of chemical evolution (Pagel 1997). This led to the idea that very shortly after the Big Bang and some time before the formation of the first galaxies ($z \sim 3$), a generation of stars polluted the universe with metals (Cayrel 1986). Recent metal-poor stellar count surveys in the halo and thick disk of the Galaxy (Beers, Preston & Shectman 1985, 1992) support this scenario, finding only a handful of stars with [Fe/H]≤ -3[1]. The observational evidence of a very low number of metal-poor low-mass stars suggests that the very first star formation episode was biased towards large stellar masses. Extremely low-mass metal-poor stars are not seen simply because they did not form, i.e. if Population III were made up of very massive rapidly evolving stars, there would be no possibility of observing them today.

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[1]In this work we use the standard notation [X/Y]$\equiv$log $(X/Y)_{\rm object} - \log(X/Y)_\odot$ for any chemical species

The existence of Population III is related to many important issues. This population of stars could play an important role in the reionization of the universe (Miralda-Escudé & Rees 1998; Gnedin 2000; Fan et al. 2000) compensating for the fact that the known populations of quasars and star-forming galaxies are not sufficient to account for the required number of ionizing photons at $z \geq 5$. Alternatively, massive remnants (black holes) as the end-products of these primordial stars could have been the progenitors of the current active galactic nuclei, while the less massive remnants (ancient white dwarfs) could have made a contribution to the MACHO population found in the halo of our galaxy (Méndez & Minniti 2000; Alcock, C. et al. 2000; Laserre et al. 2000) although this contribution is strongly limited by the observed white-dwarf luminosity function as well as by energetic arguments (Isern et al. 1998, 1999). Obviously, the real significance of Population III stars in the above issues is determined by the nature of the initial mass function (IMF) of the first generation of stars.

The idea of a pregalactic metal enrichment has become increasingly important in recent years because of the discovery of intergalactic metals in Ly-α forest clouds ($N(HI) \leq 10^{17}$ cm^{-2}) at $z = 3 - 3.5$ showing metal abundances of $Z \sim 10^{-3} - 10^{-2} Z_{\odot}$ (Songaila 1997; Cowie & Songaila 1998; Ellison et al. 2000). Sargent et al. (1980) were the first to identify the Ly-α forest with a population of primordial hydrogen clouds in pressure equilibrium with a hotter, expanding intergalactic medium (IGM). This picture, however, has changed recently to one in which the Ly-α forest is, in fact, the IGM at very early epochs. Therefore, these high redshifted clouds are believed to be essentially composed of unprocessed material from which the galaxies were formed. However, the gas producing the Ly-α forest is not pristine since a significant fraction of the detected lines are associated with C IV absorptions at $\lambda\lambda 1548, 1550$ Å (Tytler et al. 1995; Cowie et al. 1995; Songaila & Cowie 1996). The carbon abundance implied by these detections is [C/H]~ -2.5, although with an important dispersion within the forest (see e.g. Borksemberg et al. 1998). Whether the metals found

have a local origin associated with the Ly-α lines observed, or are due to an early episode of star formation (Population III) is still unclear. The answer to this question might come from metal abundance studies in very low density clouds (N(H I)$\leq 10^{14}$ cm^{-2}). However, different investigations have reached conflicting conclusions. Lu et al. (1998) concluded that there is a sudden decrease of the C abundance at low column densities ([C/H]≤ -3.5 for N(H I)$< 10^{14}$ cm^{-2}). Cowie & Songaila (1998), however, claimed a roughly constant C IV abundance distribution all the way down to Ly$-\alpha$ optical depths $\tau(\mathrm{Ly}-\alpha) \sim 0.5-1$. More recently, Ellison et al. (2000) have shown that the differences in redshift and velocity dispersion between Ly-α and C IV absorptions prevent us, at present, from answering of whether there is a uniform degree of metal enrichment down to the lowest values of N(H I).

An indirect way to infer the possible existence of Population III and the nature of its stellar mass function is to search for the imprints that could have been left in the IGM and/or in the subsequent generation of stars formed from the material ejected, that is: the *chemical* imprint. In this paper we reexamine the issue of the chemical pollution that could have originated Population III. To do so, we make use of strictly zero metal ($Z = 0$) stellar models in the mass range $3 \leq m/M_{\odot} \leq 200$ (see below). As an output, these models predict stellar yields for a number of significant isotopes which are the result of the nucleosynthetic processes occurring during the evolution of the stars. These processes include those occurring in the thermal-pulsing AGB phase (TP-AGB) for the intermediate stellar mass range ($3 \lesssim m/M_{\odot} \lesssim 8$), in type II supernova (SNII) explosions ($m \gtrsim 8$ M$_{\odot}$) and in very massive objects (VMO, $m \gtrsim 100$ M$_{\odot}$).

The paper is structured as follows: The observational constraints used to limit our model predictions are discussed in section 2. The stellar yields for zero-metal stars are presented in section 3. Section 4 describes the IMF proposed for Population III. In section 5, we use these tools to study the chemical consequences from a burst of Population III stars

and from a simple chemical evolution model. Our conclusions are summarized in section 6.

2. The observational constraints

The main observational constraint concerns the detection of metals in the Lyman-α forest spectra of distant QSOs. Since the Ly-α forest is being interpreted as intergalactic clouds, containing slightly contaminated primordial material, there must be some mechanism of mildly polluting them. Whether an early episode of pregalactic star formation (Population III)[2] is required or not to explain these abundances is still unclear. As mentioned in §1, the key factor might be whether C IV lines continue to be seen in the Ly-α clouds of decreasing H I column density. Note, that a considerable fraction of the metals detected in the Ly-α forest systems might have been produced by non zero-metal stars in already formed galaxies, and eventually ejected into the IGM by galactic winds. Here, we will assume as a *working hypothesis* that the metal contamination observed in the Ly-α forest clouds is due to a pregalactic population of stars, i.e. Population III stars. Observations by Cowie & Songaila (1998), Songaila (1997) and Ellison et al. (2000) in the direction of highly redshifted QSOs have revealed line absorptions due to C, N, O and Si. Although the abundances derived are sensitive to ionization corrections (Schaerer, Izotov & Charbonnel 2000), these studies obtained [C/H]~ -2.5 and [Si/H]~ -2.3 with a scatter of about a factor of 3 in systems with $z = 3 - 3.5$ (no abundance ratios are given for N and O). Scaling these values to the solar metallicity implies that these systems have a metallicity of Z$\sim 4 \times 10^{-3}$ $Z_{\odot}$, or [Fe/H]~ -2.4. Note, however, that current observational techniques used to derive metal abundances in the Ly-α systems cannot properly account for the inhomogeneity of the IGM and, therefore, these techniques probably give only lower

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[2]We consider the Population III objects as *stars* with $Z = 0$.

limits on Z. Nevertheless, as mentioned above, here we adopt these abundance ratios as the typical level of chemical enrichment in the IGM produced by the hypothetical Population III.

Our second observational constraint comes from the metal absorptions detected in very distant systems with a high density of H I, N(H I)$\gtrsim 2\times10^{20}$ cm^{-2}, i.e.: the damped-Lyman systems. In modern cosmological theories, damped systems are assumed to be more highly evolved objects than the Ly-α forest and probably represent the earliest stages of the present-day disc galaxies (Wolfe 1995). These systems provide the best opportunity to measure abundances of different elements at high redshifts. Numerous abundance studies in these systems [see Pettini (1999) for a compilation] have clearly established that the cosmic metallicity inferred in neutral gas does not evolve significantly from $z\sim1$ to 4 although the unweighted metallicity exhibits a statistically significant decrease with increasing redshift (Prochaska, Gawrser & Wolfe 2001). The mean metal abundance in these systems between $z=1-4$ is $Z\sim6\times10^{-2}$ Z$_{\odot}$ (or [Fe/H]~-1.2), although with a range of almost two orders of magnitude in the metallicity attained by different damped systems at essentially the same redshift. The main difficulty encountered in these abundance studies is to account for the fraction of each element that has been removed from the gas phase to form interstellar dust. Despite this, most of the abundance ratios measured are similar to the abundance pattern expected from solely SNII pollution (Lu et al. 1998), although not all the abundance ratios derived follow this SNII pattern (Prochaska & Wolfe 1999; Pettini 1999). The limitations introduced by these abundance ratios upon the enrichment from Population III are not clear, since if they are considered more evolved objects, the abundance pattern in damped systems may be the result of several episodes of star formation. Therefore, it does not reflect the result of the very first metal pollution. We note, however, that no damped system is observed with [Fe/H]<-2.7 (Prochaska & Wolfe 2000).

Finally, the abundance ratios found in the most extremely metal-poor stars in our galaxy constitute another observational constraint to the early chemical evolution. For instance, one of the most striking results of these studies is that $\sim 25\%$ of the stars with [Fe/H]$\lesssim -2.5$ exhibit large carbon and nitrogen abundances relative to iron, [C,N/Fe]$\gtrsim 1$ (Norris, Beers & Ryan 2000; Rossi, Beers & Sneden 1999). Many of these metal-poor carbon/nitrogen enhanced stars also exhibit extremely high abundances of neutron-capture elements (Sneden et al. 1996; Bonifacio et al. 1998; Depagne et al. 2000; Sneden et al. 2000; Hill et al. 2000; Spite et al. 2000). Despite the fact that their evolutionary status is not completely known, many of them are certainly unevolved (or turn-off) stars for which the hypothesis of internal pollution can be safely discarded (note that many of these stars present Li abundances similar to those of the Spite plateau). One might think that the entire CN-enhancement observed in these Population II stars is the result of the mass transfer across a binary system which formerly contained an AGB star (in fact, many of them present radial velocity variations); there are, however, several reasons for believing that this might not always be the case. The fact that $\sim 25\%$ of the most metal-deficient stars are CN-enhanced comprises a stringent requirement on the fraction of such systems that form binaries with the right configuration for the mass transfer to occur. Furthermore, not all of these stars present abundance patterns with the s-process elements thought to occur in AGB companions. The abundance patterns in these stars might well be content the key to understanding the nucleosynthetic processes in the very early Galaxy before these extremely metal-deficient stars formed.

3. The IMF for Population III stars

The issue of the IMF for the first generation of stars has received particular attention (see e.g. Matsuda, Sato & Takeda 1969; Carberlg 1981; Silk 1983). Since metals are the

most important coolants in present-day star formation, these studies have emphasized the importance of the radiative cooling by H-based molecules because the primordial gas was deficient in heavy elements. Current models predict that the first bound systems capable of forming stars appeared in the history of the universe at redshifts between 50 and 10 and had masses between 10^5 and 10^8 $M_\odot$ (see e.g Miralda-Escudé 2000). Depending mainly on the ratio between the time scale for radiative cooling and heating due to the gravitational collapse, these structures could further fragment into clumps with smaller masses. These simulations show that typical fragmentation into clumps occurs with masses in the range 10^2-10^3 $M_\odot$, but due to the relatively low resolution used in these studies, there is no clear consensus on whether these structures can fragment into still smaller mass clumps. This controversy seems to originate from oversimplified assumptions like a homogeneous, pressure-less and/or spherical collapse. The minimum mass fragment that could form is of special relevance because of the feedback effects. If the typical protostar fragment formed had a large mass ($\sim 10^2$ $M_\odot$), its high luminosity would contribute to the rapid heating of the collapsing clump, inhibiting further fragmentation. Additionally, the final fate of these high mass objects would probably be a very energetic phenomenon (SNII-like or hypernova explosion). The large energy deposited in the gas during this event could be large enough to completely disrupt the clump, again avoiding further star formation. Thus, the typical mass of the collapsed fragment not only determines the IMF but also the period of time during which the first star formation episode occurred.

In this respect, Uehara, Susa & Nishi (1996) set a minimum fragment mass at about the Chandrasekhar mass (> 1.4 $M_\odot$). This is an important result because it implies that we should see no metal-free stars at the present time, since all of these stars should by now have evolved. Yoshii & Saio (1986), based on the opacity-limited fragmentation theory, derive an IMF that is steeper in the high stellar mass range than a Salpeter-like IMF; the exact slope, however, critically depends on the mass-luminosity relation assumed

for the zero-metal protostars. An interesting result from the Yoshii & Saio calculations is that the IMF derived would have a maximum around the intermediate stellar mass range (3-8 $M_{\odot}$). Very recently, Nakamura & Umemura (2000) performed multi-dimensional hydrodynamic simulations of the collapse and fragmentation of filamentary primordial clouds. These simulations show that, depending upon the initial density of the cloud, the IMF for Population III stars is likely to be bimodal. Gas filaments with initial densities lower than $\sim 10^5$ cm^{-3} tend to fragment into structures with masses larger than several tens of $M_{\odot}$ ($\sim 10^2$ $M_{\odot}$), while initially denser filaments ($n \gtrsim 10^5$ cm^{-3}) experiment more effective H_2 cooling and fragment into structures of $\sim 1 - 2$ $M_{\odot}$. The relative peaks of this bimodal IMF would be a function of the collapse epoch in such a way that during the first epoch the dominant peak would be around 2 $M_{\odot}$, while as the star formation proceeds and the collapsing clump heats up, the Jeans mass would be displaced to larger masses, moving the peak to $\sim 10^2$ $M_{\odot}$.

The above mentioned studies basically compile the proposed IMFs for Population III stars in the literature. In summary: i) there are physical arguments for assuming that the slope of the present IMF has changed in time, ii) the first star-forming clouds typically fragmented into massive clumps of $10^2 - 10^3$ $M_{\odot}$, iii) there exists the possibility of further fragmentation into smaller masses, producing an IMF peaking at about the intermediate stellar mass range. Support to these facts hasbeen recently given by Hernandez & Ferrara (2001). In the framework of the standard hierarchical clustering scenario of galaxy formation, these authors show that the IMF of the first stars was increasingly high mass biassed towards high redshifts: at $z \sim 9$ the charactheristic stellar mass being 10-15 $M_{\odot}$. Therefore, we will restrict our analysis to the IMFs that cover the above properties. In fact, we use the IMFs proposed by Yoshii & Saio, referring to them as YSa if a relation mass-luminosity in the form $L(m) \propto (m/M_{\odot})^{\beta}$ with $\beta = 1.5$ is adopted, or YSb if $\beta = 3$. We also use the bimodal IMF proposed by Nakamura & Umemura and, in a similar way, we

consider two cases, depending on the position of the peaks: NUa if the peak at low stellar mass is the dominant one or NUb if the peak at large mass dominates. For comparison, we contrast the results with those obtained from the canonical Salpeter (1955) IMF. Figure 1 shows the IMFs used in the mass range 1-10^3 $M_\odot$, and clearly demonstrates how these IMFs differ [3].

4. The stellar yields

Recent theoretical analysis of the evolution of Population III stars predicts that the fate of metal-free stars can be classified as follows: (1) Stars with initial mass $m \gtrsim 250$ $M_\odot$ collapse to a black hole (BH) with no metal ejection (Ober, El Eid & Fricke 1983; Heger et al. 2000). (2) Stars in the mass range $100 \lesssim m/M_\odot \lesssim 250$, usually termed very massive objects (VMO), are disrupted by electron-positron pair instability leading to a type II supernova-like event (pair creation supernovae, PCSN) and eject metals leaving no compact remnant behind. (3) Stars with initial mass in the range $40 \lesssim m/M_\odot \lesssim 100$ probably collapse into a BH without metal contribution (Woosley & Waever 1995, but see below). (4) Stars in the range $10 \lesssim m/M_\odot \lesssim 40$ give a type II supernova (SNII) event (Woosley & Weaver 1995; Limongi, Chieffi & Straniero 2001; Limongi, Straniero & Chieffi 2000) and finally. (5) Stars with initial mass $m \gtrsim 1$ $M_\odot$ and lower than the minimum mass for carbon ignition (~ 8 $M_\odot$) will pass through the AGB phase (Fujimoto, Ikeda & Iben 2000; Chieffi et al. 2001) leaving a white dwarf (WD) as the stellar remnant.

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[3]The IMFs are normalized as $\int_{m_{low}}^{m_{up}} \phi(m)dm \equiv 1$, where m_{up} and m_{low} are the upper and the lower stellar mass limit, respectively. Note that the upper limit varies depending upon the IMF adopted. From the Uehara, Susa & Nishi (1996) results we have adopted $m_{low} = 1$ $M_\odot$ in all the IMFs.

The nucleosynthesis products from intermediate mass stars (IMS) ($1.5 \lesssim m/M_\odot \lesssim 8$) are of special interest here since the IMF for Population III stars might peak in this mass range. Note that a star with initial mass around 7-8 $M_\odot$ has a lifetime ($\sim 10^7$ yr) only slightly larger than that of a typical SNII progenitor and therefore will contribute to IGM enrichment shortly afterwards. Due to the peculiarity of the $Z = 0$ stellar evolution, appropriate yields are highly necessary. Previous calculations of the stellar yields in metal-poor IMS were obtained from stellar models with no primordial composition, $Z \sim 10^{-4} Z_\odot$ (Marigo, Bressan & Chiosi 1998; Van den Hoek & Groenewegen 1997). Moreover, these yields were obtained from synthetic approximations after the end of He-burning without having taken into account the evolution during the TP-AGB phase. In fact, the existence of third dredge-up (TDU) episodes and thermal pulses (TP) in this phase plays a crucial role in determining the stellar yields from IMS. Recently, Chieffi et al. (2001) performed a detailed analysis of the evolution of zero metal IMS. Using the evolutionary code FRANEC (Chieffi, Limongi & Straniero 1998) these authors found, at variance with previous studies, that these stars do experience TP during the AGB phase. As a consequence, TDU episodes occur and the stellar envelope may be enriched with fresh ^{12}C, ^{14}N and ^{16}O during this phase. The most important result from this study is that these stars become C-rich (i.e. carbon stars) and N-rich and can eject important amounts of these elements at the end of their evolution. The yields from these stars are, however, sensitive to the modeling of the mass-loss rate during the AGB phase. In fact, it is the mass-loss rate that finally determines the duration of the AGB phase since it limits the number of TPs and, therefore, the number of TDU episodes. Both mass loss and dredge up efficiency could be deduced by the observed properties of the disk AGB population, but little is known of these phenomena in very metal-poor stars. We note, however, that the increase of the heavy elements in the envelope, caused by the TDU in Population III AGB stars, could reduce the difference with respect to the more metal-rich AGB stars. The yields of

intermediate mass stars shown in Figure 2 have been obtained by assuming a Reimers mass loss rate with $\eta = 4$. This is considered a reasonable average mass loss rate for Population I intermediate mass AGB stars (see van den Hoeck & Gronewegen 1997). We emphasize that the ^{14}N production from IMS is quite different from the value adopted here if a different value of η is assumed. For example, assuming $\eta \approx 1$ the ^{14}N yield decreases by a factor ~ 3. On the other hand, Chieffi et al. (2001) also show that in the most massive models ($m > 4$ $M_\odot$), ^{7}Li can also be synthesized via hot bottom burning by the Cameron & Fowler (1971) mechanism in the same way as occurs in higher metallicity models (Sackmann & Boothroyd 1992). The Li mass fraction in the envelope can reach peak values $\sim 10^{-8}$, although the final Li yield would be lower than this value because of the progressive ^{3}He consumption and Li depletion at the base of the envelope during the AGB phase.

Concerning the lowest mass range among IMS ($1.5 \lesssim m/M_\odot \lesssim 3$), Fujimoto, Ikeda & Iben (2000) have shown that these stars develop TP and also become C and N-rich. Unfortunately, these authors did not compute yields from this mass range. However, we believe they can be omitted from our analysis, for the following reasons: i) Most studies of the fragmentation of primordial gas agree that objects with mass $m < 2$ $M_\odot$ are very difficult to form. ii) We are mainly interested in the very early chemical enrichment of the IGM. Stars with $m < 3$ $M_\odot$ have a long lifetime and, if they formed, would only contribute at very late times in the chemical evolution of the IGM.

The adopted stellar yields for the mass range $10 \lesssim m/M_\odot \lesssim 40$ are taken from Limongi, Straniero & Chieffi (2000). These yields are based on presupernova evolutions computed with the FRANEC code plus a simulated explosion based on the radiation dominated shock approximation (Weaver & Woosley 1980). The location of the mass cut has been chosen by requiring that ~ 0.05 $M_\odot$ of ^{56}Ni are ejected by each stellar model. This amount of Ni is very similar to that used to explain the observational properties of the SN 1987A. Let us

remind that since the location of the mass cut is still theoretically very uncertain, the yields of the elements mainly produced at the bottom of the mantle will largely depend on the adopted mass cut. If the ejected amount of ^{56}Ni ranges between ~ 0.001 and ~ 0.2 M$_\odot$, the mass cut remains confined within the region exposed to the complete explosive Si burning and hence only the elements produced in this region, i.e., iron, cobalt and nickel, would be significantly modified by changing the mass cut location (see Limongi, Chieffi & Straniero 2001). On the contrary, carbon, nitrogen and oxygen yields, which are synthesized in a more external layer of the star, where the modifications induced by the explosive burning are less important, are more robust. Obviously, the abundance ratios of any element with respect to Fe in the ejected matter vary according to the assumed ejected mass of iron. It is important to emphasize that the yields used here in the mass range $3 \lesssim m/M_\odot \lesssim 40$ are computed in a homogeneous and consistent way. On the other hand, the final fate of stars in the mass range 40-100 M$_\odot$ is highly uncertain because it is not clear if they collapse to a black hole or not. Woosley & Weaver (1995) (see their Figure 7) found that zero metal stars reach the moment of the final core collapse with a structure much more compact than that of more metal rich ones. Hence, they found that stars more massive than about 40 M$_\odot$ should collapse into a BH under the assumption that the energy delivered to the star after the bounce does not significantly depend on the initial mass. In this first study we adopt this scenario while in a forthcoming one we will investigate how the results change by assuming that also stars more massive than 40 M$_\odot$ contribute to the chemical enrichment of the intergalactic medium.

Unfortunately we do not yet have stellar yields computed in the same way from the FRANEC code for VMOs. As far as we know, the only complete set of stellar yields available in the literature for VMOs are those of Ober, El Eid & Fricke (1983). These authors performed full evolutionary calculations of zero-metal stars with initial mass in the range $100 \lesssim m/M_\odot \lesssim 250$ and computed the nucleosynthetic products due to incomplete

oxygen burning in PCSN. One of the most interesting results from these computations is that few or no iron-peak elements ($50 < A < 60$) are produced in the PCSN process. This result contrasts, however, with the more recent calculations of Arnett (1996) and Heger et al. (2000). Arnett (1996) studied the explosion of very massive CO cores of different mass and found that important quantities of iron-peak elements can be ejected, depending again on the mass-cut position. Computations by Heger et al. (2000) in a ~ 70 $M_\odot$ CO core (corresponding to a star of initial mass ~ 150 $M_\odot$) produce the same figure. Nevertheless, we have compared the stellar yields computed by Ober, El Eid & Fricke (1983) with those by Arnett (1996) and Heger et al. (2000) for the same CO core model and found an excellent agreement (differences less than a factor of 2) except, as mentioned previously, for the iron-peak elements. Because of the high uncertainty related to the iron yield in VMOs, we decided to adopt that of Arnett (1996). We note that theoretical interpretations of the element ratios (in particular the low Ba abundances and the high dispersion in the [Ba/Fe] ratio) found in the most metal-poor stars of our galaxy (McWilliam et al. 1995; Sneden et al. 1998), might indicate that a source other than SNII must exist to produce the Fe observed at [Fe/H]≤ -3. Wasserburg & Qian (2000a) attribute this source to the first VMOs formed from the Big Bang debris.

Figure 3 shows the yields of the significant elements finally adopted in the stellar mass range computed by us.

5. Chemical evolution calculations

In this section we apply the computed yields and the IMFs proposed for the zero-metal stars to study the early chemical enrichment of the IGM by means of two different and simple approaches. In both approaches we consider the entire universe at high redshift as a one-zone system where the gas exists in a *homogeneous* chemical phase. From this gas

with primordial composition, Population III stars form whether isolated, or within dense clouds with mass $10^5 - 10^8\ M_\odot$ (see §1). In any case, we assume that the outflow from the Population III stars is instantly and evenly mixed with the primordial IGM gas. More realistic models describing the mechanisms from which material processed in stars formed in primordial clouds is injected and mixed into the IGM, are discussed in Ferrara, Pettini & Shchekinov (2000); Madau, Ferrara & Rees (2000). This is, however, beyond the scope of the present paper.

First, we consider a single *burst* of star formation. In this approach the stellar ejecta is incorporated instantaneously into the IGM and there is no further episode of star formation, i.e.: the ejecta are not incorporated into any second generation of stars. The second case is a simple chemical evolution model where the stellar lifetimes are considered explicitly. The model is evolved for 10^8 yr in time steps of 10^5 yr to resolve the small lifetimes of the VMOs, starting at the onset of the Population III star formation. This allow us to clearly distinguish between the role played by VMO, massive stars and IMS respectively, in the pollution of the IGM along the evolving cosmic time. Note that a time $\sim 10^8$ yr is roughly the lifetime of a zero-metal star of 3-4 $M_\odot$. Although in this second approach several generations of stars are created, and the ejecta of one generation is mixed into the next generation of stars, the evolution time considered in the model is short enough to minimize this effect (see below). To give some numbers, placing the very first star formation episode at redshift $z \sim 10 - 20$ in a universe with $\Omega = \Omega_M + \Omega_\Lambda = 1$ and $H_o = 65$ km/s/Mpc, a time interval $\Delta t \sim 10^8$ yr corresponds to a redshift $z \sim 8.5 - 15$, respectively. For comparison, $z \sim 3$ which is assumed to be the epoch of galaxy formation, corresponds to $\Delta t \sim 2 \times 10^9$ yr after the Big Bang.

5.1. The burst model

To compute the chemical enrichment of the IGM due to a single burst of star formation we proceed as usual. Initially all the baryons in the universe are in gaseous form with a comoving density ρ_b. During the star burst a fraction $p \equiv \rho_*/\rho_b$ (where p is the star formation *efficiency*) goes into stars. Once the generation of stars have died, a fraction R of their mass is returned into the IGM as processed gas. This fraction is

$$R = \int_1^{m_{up}} \phi(m) R_{ej}(m) dm \tag{1}$$

where $R_{ej}(m)$ is the mass fraction of a star of mass m ejected when the star dies. This fraction varies depending on the adopted IMF, $\phi(m)$: 0.67, 0.86, 0.82, 0.4 and 0.45 for the Salpeter, YSa, YSb, NUa, NUb IMFs, respectively. The choice of the IMF also determines the upper mass limit m_{up} (see Figure 1). It is easy to show that the comoving density of the gas after the burst is given by

$$\rho_{gas} = \rho_b - (1 - R) p \rho_b \tag{2}$$

On the other hand, if the initial gas density of each isotope is given by $\rho_i^o = \rho_b X_i^o$, where X_i^o is its primordial abundance in mass fraction, the density of a given isotope after the burst is

$$\rho_i = \rho_i^o - \rho_* X_i^o + \rho_i^{eject} \tag{3}$$

where ρ_i^{eject} is the gas density of the specific isotope in the material ejected by the generation of stars. We thus define the enrichment of the IGM in the isotope i as

$$\Delta X_i = \frac{\rho_i}{\rho_{gas}} - X_i^o \quad (4)$$

For isotopes with no primordial composition $X_i^o = 0$. After some simple algebra from equations (2) and (3), the chemical enrichment can be written.

$$\Delta X_i = \frac{p}{[1-(1-R)p]}(y_i - X_i^o) \quad (5)$$

where y_i is the stellar yield defined as the mass fraction of the total mass returned by a generation of stars in the form of the isotope i.

The results from the combined effect of the stellar yields and IMFs for Population III are summarized in Table 1. The second column gives the total metallicity Z reached in the material ejected by the star burst (i.e., without considering the dilution with the metal-free IGM gas) relative to the solar metallicity ($Z_\odot = 0.0189$). Column three shows the maximum efficient factor p allowable for each IMF so as not to surpass the maximum metallicity observed in the Ly-α forest, $Z \sim 4 \times 10^{-3} Z_\odot$. Note that quite low values of p are allowed for all the IMFs. The most restrictive p values are those obtained for the NUa & NUb IMFs because of the high metal pollution from VMOs ($Z/Z_\odot > 1$, see column two)[4]. These low values of p contrast with the current estimate of the efficient factor in regions of star formation in the Galaxy, $p \lesssim 10^{-2}$, or in other spiral galaxies (Kennicutt 1998). However, for any IMF choice in Table 1 the corresponding p factor is large enough for the

[4]As mentioned in §2, the metallicity measured in the Ly-α forest systems is uncertain and may well be lower limits. In such a case, the values of p in Table 1 should be considered also as lower limits. In fact, Hernandez & Ferrara (2001) and Ciardi et al. (2000), estimate slightly larger values of p than those in Table 1 from different analyses, which would be in agreement with this figure.

Population III to have played an important role in the reionization of the universe before $z \sim 6-7$ (see e.g. Bromm, Kurdritzki & Loeb 2000).

We can also use the star burst model to estimate the contribution of the stellar remnants from Population III to the baryonic matter density. It is a simple matter to show that the comoving density of stellar remnants ρ_{sr} is related to the baryonic density by

$$\rho_{sr} = (1-R)p\rho_b \tag{6}$$

Then, if we use Ω_{sr} to describe the density of stellar remnants in units of the critical density ($\rho_{crit} = 2.77 \times 10^{11} h^2$ $M_\odot$ Mpc^{-3}),

$$\Omega_{sr} = (1-R)p\Omega_b \tag{7}$$

where Ω_b is the baryonic density in units of the critical one. In column four of Table 1 we show Ω_{sr} derived from equation (7), the corresponding p value compatible with the metallicity limit requirement (see §2), assuming $\Omega_b = 0.019$ and $H_o = 65$ km/s/Mpc. The values of Ω_{sr} are quite low, representing only a very small fraction of Ω_b for any IMF choice ($\Omega_{sr}/\Omega_b < 3 \times 10^{-3}$). This can be seen more clearly in Figure 4, where we report the abundance of C versus Ω_{sr} obtained under different assumptions for the mass function from equation 5 (after a straightforward transformation). The two vertical lines bound the region compatible with the baryonic mass budget implied by a Galactic halo interpretation of the LMC MACHO events (Fields, Freese, & Graff 1998), whereas the horizontal one indicates the abundance measured in the most metal-poor Lyman-α forest system. Clearly, for a $\Omega_{sr} \gtrsim 10^{-3}$ model predictions are far beyond of the observational limits for any mass function. The low values of Ω_{sr} required for our analysis to be compatible with the observational constraints are even more limiting than those imposed in other studies.

For instance, Madau & Pozzetti (2000) impose a limit from the observed extragalactic background light, $\Omega_{sr}/\Omega_b < 5 \times 10^{-2}$. The strong limitation on Ω_{sr} that we found here coincides with the conclusion by Fields, Freese & Graft (2000) in a similar nucleosynthesis analysis, i.e. that the contribution of the stellar remnants from an ancient generation of stars to the baryonic dark matter would have been insignificant.

Columns 5 to 11 of Table 1 give the IGM abundances relative to the Solar System values (Anders & Grevesse 1988) for certain elements after the star burst. These abundance ratios are computed from equation (5) using the corresponding efficient factor p (column two) for each IMF entry. Remarkably high [C,N/H] values result from the Salpeter, YSa and YSb IMFs, due to the large C and N production by zero metal IMS, which play an important role in these IMFs. In contrast, note the low [N/H] value obtained in the Nakamura & Umemura cases. This is because the N yield from VMOs is very small. However, the [Fe/H] ratio obtained in the Nakamura & Umemura cases is large if Arnett's (1996) iron yield in VMOs is used. Si and Ca production is also important in these objects in such a way that [Si,Ca/Fe]$\gtrsim 0$ although, [C,N,O,Mg/Fe]$\lesssim 0$. Of course, if the iron yield in VMOs from Ober, El Eid & Fricke (1983) is used, the [Fe/H] ratio from equation 5 in the Nakamura & Umemura cases would be much lower ([Fe/H]~ -6) and, in consequence, extremely high [X/Fe] ratios are obtained for any chemical species in Table 1.

Obviously, the strongest constraints that can be imposed on the nature of the Population III IMFs come from the ratios between different elements. Unfortunately, the shortage of abundance measurements in Ly-α forest systems still prevent us from drawing limiting conclusions from the results in Table 1. Note in addition, that currently is still under debate whether the abundances measured in the high redshiftz systems reprensent the chemical imprint of the Population III stars or not (see §2). Even if Population III stars existed, these abundances could have a nonnegligible contribution from non-zero

metallicity stars. Having this in mind, from Table 1 we can see that the best IMF choice compatible with the observational constraints discussed in §2 would be that of YSa, i.e. an IMF peaked in the high mass range (5-7 $M_\odot$) of IMS, also including massive stars with a Salpeter-like slope but without VMOs (see Figure 1). In this case [C/H]= -2.3 and [Si/H]= -2.4 are obtained, in full agreement with the single abundance measurement of these elements in the Ly-α forest systems. The large [C,N/Fe] ratios obtained with the YSa IMF are also compatible with the large C and N overabundances found in some extremely metal-poor stars (see references in §2). Furthermore, small overabundances of α-elements [O,Mg,Si,Ca/Fe] are also obtained with this IMF, of the order of those derived in damped Ly-α systems. In contrast, the [C,N/O]>0 ratios obtained with an IMF that is heavily weighted in the IMS range (cases YSa and YSb mainly) contradict the abundance ratios ([C,N/O]<0) found in Population II stars [note however that the O abundance in these stars is still very controversial, see e.g. Boesgaard et al. (1999); Israelian et al. (2001)]. In this respect it would be very interesting to derive O abundances in the Ly-α forest systems and in the extremely metal-poor stars with large [C,N/Fe] ratios. This might determine whether the IMS were present in the very first generation of stars.

Finally, the last column of Table 1 shows the Li abundance by number (Li/H) expected in the material processed after the burst. Since the only evidence of a stellar production of Li comprises the high Li abundances measured in some AGB stars (Abia et al. 1991), we have only considered the Li production by IMS, without taking into account the possible production by zero-metal SNII through the ν-mechanism (Woosley & Weaver 1995). From Table 1 it is clear that no significant Li contribution from zero-metal IMS to that produced in the Big Bang is expected from any IMF choice. In fact, the Li enrichment ΔX_7 computed from equation (5) is negative for any value of p assuming $X_7^o \approx 10^{-9}$.

5.2. The evolutionary model

We have adopted the Abia, Isern & Canal (1995) chemical evolution package, in order to follow the evolution of some isotopes over time. Current knowledge of star formation history at very early epochs in the evolution of the universe is very limited (Steidel et al. 1999; Madau et al. 1996; Hopkins, Connolly & Szalay 2000). The best estimate available at present indicates a roughly constant star formation activity between $z \sim 1-4$ but no data exists for $z > 5$. Therefore, as it is usually done, we have assumed a star formation rate proportional to the comoving gas density $\psi(t) = \alpha\rho^n_{gas}(t)$, where $\alpha = 2$ Gyr^{-1} is the astration parameter and $n = 1$. Note that the computed abundance ratios [X/Y] are nearly insensitive to the adopted star formation rate but they do depend upon the stellar yields and on the IMF adopted. In fact, parallel calculations with other α and n values were made to ensure that our calculations were not dependent upon these parameters. As mentioned previously, we have followed the evolution of the abundance ratios for 10^8 yr from the onset of the primordial star formation. We have not considered the role played by type Ia supernovae since these objects are usually thought to come from longer lifetime progenitors [5]. In any case, decisions regarding of the IMF and the law for the star formation rate have, however, important consequences for the present-day type Ia SN rate (see Canal, Isern & Ruiz-Lapuente 1997). The stellar lifetimes have been obtained by means of the same models used to derive the stellar yields. The computed stellar models extend from the pre-main sequence until the thermally pulsing AGB phase for the IMS, or until the Si-melting in the massive star range. For VMOs we have extrapolated our numerical lifetime-stellar mass relation to the corresponding mass range. For example, the lifetimes of stars with initial masses of 4, 25 and 120 $M_\odot$ are 114, 7.8 and 1 Myr, respectively. Due to the very

[5]This is not strictly true in the case of a Red Giant accreting mass on a WD generated by an intermediate mass progenitors.

short lifetimes of massive stars and VMOs, several generations of these stars would form during our adopted evolution time (10^8 yr). Because of the progressive pollution of the IGM, the subsequent generations of stars would form with a non strictly zero metallicity. Although we also have yields for massive stars computed with the FRANEC code for different metallicities, as far as we know there is no mention in the literature of this kind of computation for VMOs [setting aside the possibility that these objects may form with a non-zero metallicity (see however Figer et al. 1998)]. Therefore, for the sake of homogeneity in our computations, we did not consider this effect, i.e. the metallicity dependent yields. We believe nevertheless, that this inconsistency in the model would only have a minimal effect due to the very short time interval considered.

In Table 2 we show the total metallicity reached in the IGM for the different IMFs at several values of the cosmic time. We consider this metallicity as typical mean values since at very early epochs the pollution of the IGM was very inhomogeneous, probably occurring through the mixing of cloud patches already contaminated with metals (Argast et al. 2000). We emphasize that the metallicity values in Table 2 are extremely dependent on the star formation rate history assumed. What is important in Table 2 is the comparison between the results obtained with different IMFs at a given cosmic time. As expected from Figure 1, the evolution of the metallicity obtained in the Salpeter case is between that of the YSa and YSb cases. Note the very low value of $Z/Z_{\odot}$ in the YSb case at log t= 6.5. This is due to the steeper slope of this IMF for the high stellar mass range. In contrast, at log t$\sim$ 8 the YSa IMF presents an important degree of metal enrichment due to the smoother than conventional slope of this IMF for the massive stars (see Figure 1). The high metallicity value reached $Z \sim 3 \times 10^{-2}$ $Z_{\odot}$ ([Fe/H]~ -1.7) at log $t \sim 8$ in the YSa case is similar to that of the low metallicity tail in the metal distribution of thick disk stars in our galaxy (Norris & Ryan 1991). For the Nakamura & Umemura IMF cases, the metallicity in the IGM increases rapidly at very early times due to the contamination from massive stars

and VMOs, but the pollution is not as rapid at later times as that in the Salpeter and/or Yoshii & Saio IMFs. This is due to the lesser importance of IMS which contribute at late in the two former IMFs. For the Salpeter, YSb and NUa cases a metallicity similar to that of the most metal-poor stars in our galaxy is achieved at log t$\sim$ 8: [Fe/H]≈ -2.5, -2.7 and -3.0 are obtained, respectively. Interestingly, these values are of the order of those predicted in the prompt-enrichment model for the early galaxy proposed by Wasserburg & Qian (2000a,b).

Figure 5 shows the evolution in time of several abundance ratios for the different IMFs. We plotted the abundance ratios against the cosmic time instead of [Fe/H] as this abundance ratio is very dependent upon the model parameters. The abundance ratios obtained in our model for a time $\sim 10^8$ yr after the onset of the Population III star formation, might be interpreted as those present in the more massive and denser collapsed structures from which the present-day galaxies would have formed, i.e. the high redshift damped Ly-α systems (see §2). From Figure 5 it can be seen that the evolutions of the abundance ratios computed in the Salpeter and YSa cases are almost equal. The sole difference appears in the [C/Fe] and [N/Fe] ratios at late times due to the more important contribution of IMS in the Salpeter case. For the YSa and Salpeter IMFs, overabundances of [C,N/Fe]$\gtrsim$ 0 are obtained at log t$\sim$ 8 as well as for the α-element ratios [O,Mg,Si,Ca/Fe]. Note the sudden increase of the [N/Fe] ratio at log t$\sim$ 7.6 which indicates the onset of the IMS contribution to the IGM metal enrichment. On the contrary, underabundances of [Mg,Si/Fe] are obtained with the YSb IMF. The reason for this is the steeper slope of this IMF in the mass range of the SNII progenitors from which these α-elements are produced. From the YSb IMF, however, a sharper increase of the [C,N,O/Fe] ratios at later times is obtained, which indicates the importance of the IMS contribution to CNO in this case (see Figure 1). In fact, [C,N/Fe]$>$ 1 are obtained at log t$>$ 7.6 for the YSb case

For the Nakamura & Umemura cases, the evolutions of the abundance ratios are equal (see Figs. 5 and 6) thus, we have omitted the NUb case from these figures for the sake of clarity. However, the corresponding evolution of the absolute abundances are rather different, as it can be seen in Table 2. Again, overabundances of α-elements are obtained for any time[6]. The evolution of the [C,N/Fe] ratio differs significantly with respect to that obtained from the Salpeter, YSa and YSb cases. At early times underabundances of C and N are predicted, in particular that of nitrogen. This is due to the very small yield of ^{14}N in zero metal VMOs. However, the large C and N overabundances at late times is again due to the production by IMS (see Figure 1). From Figure 5 it is obvious that the evolution of the [C/Fe] and [N/Fe] ratios is dramatically affected by the yields from IMS for any IMF choice. To emphasize the importance of the zero-metal IMS in the early enrichment of the IGM, in Figure 6 we have plotted the evolution of the CNO abundance ratios. Extreme [C/O] and [N/O] ratios result when an IMF that is heavily weighted around 2-4 $M_\odot$ is used (YSb, NUa and NUb cases). Note also the very low [N/O,C] ratios predicted at early times when the presence of VMOs is considered in the IMF.

How can the evolution of the abundance ratios in Figures 5 and 6 be related to observations? If we consider only the abundance ratios obtained at log t$\sim$ 8, the abundance ratio [Si/C]$\sim$ +0.2 measured toward the Ly-α forest systems (Songaila 1997) would be in better agreement with a Salpeter IMF. A steeper slope in the mass range $10 \lesssim m/M_\odot \lesssim 40$, as in the YSb case, does not seem adequate. The presence of VMOs in the primordial IMF is also favored by this [Si/C] ratio provided that an important C production from IMS is excluded. On the contrary, on the basis of the present yield calculations for zero-metal stars, the only way to obtain large [C,N/Fe]> 1 ratios is to accept an IMF peaking in the

[6]Note that in the NUa and NUb cases the [Ca/Fe] evolution refers to the combined evolution of α-elements in the mass range $32 \leq A \leq 40$ (^{32}S, ^{38}K and ^{40}Ca).

IMS range. An IMF of such a type could explain the high C and N abundance ratios found in a considerable number of extremely metal-poor stars. This, however, would imply high [C,N/O] ratios. Unfortunately, there exist no oxygen abundance determinations in these very metal-poor stars to test this hypothesis. Note that in Population II halo stars with [Fe/H]< -1.5 the observed ratios are [C,N/O]~ -0.5 (Tomkin et al. 1992). Although the O abundances are also uncertain in these stars, these low [C,N/O] ratios would be against an IMF heavily weighted of intermediate mass stars. In this respect, our conclusions are similar to those reached by Gibson & Mould (1997) using $Z \sim 10^{-4}$ $Z_\odot$ stellar yields for IMS. On the other hand, the [O/Fe] ratios derived in the most metal-poor stars in our Galaxy certainly put interesting constraints on the very early chemical evolution. With the yields for zero-metal stars used here, we did not find ratios [O/Fe]$\gtrsim 1$ as derived in several recent studies (Abia & Rebolo 1989; Israelian, García-López & Rebolo 1998; Boesgaard et al. 1999; Israelian et al. 2001; Mishenina et al. 2000) for any IMF. However, taking into account the uncertainty in the iron yield from massive and very massive stars (see §4), it is indeed possible to obtain [O/Fe]> 1 or higher at very early times by decreasing the iron yield from these stars with respect to that adopted here, by only a factor of four. The present uncertainty on the iron yield from these stars, allows such a variation.

6. Summary and conclusions

We have studied the chemical constraints imposed on the existence of a pregalactic generation of stars (Population III) by the recent abundance determinations in high redshift systems and in extremely metal-poor stars in our Galaxy. Using yields computed from stellar models ($3 \lesssim m/M_\odot \lesssim 200$) of strictly zero metal content, we have shown that a chemical enrichment to the level observed in the high redshift intergalactic medium can be easily obtained from a stellar pregalactic nucleosynthesis. We merely have to postulate

(see Table 1) that a small fraction ($p < 10^{-2}$) of primordial matter has participated in the Population III stars. As a consequence, this low pregalactic star formation efficiency strongly limits the contribution of the stellar remnants from Population III to the baryonic matter. We found $\Omega_{sr} < 10^{-3}\Omega_b$ for all of the IMFs tested. However, the present scarcity of abundance data in the high redshift universe (which are of controversial interpretation) does not yet permit us to strongly limit the IMFs currently proposed for Population III: basically, an IMF peaking in the intermediate stellar mass range ($3 \lesssim m/M_\odot \lesssim 8$) or an IMF including very massive objects ($m \gtrsim 100$ M$_\odot$). Nevertheless, at the present state of the art on stellar nucleosynthesis models, the very large C and N enhancement ([C,N/Fe]> 1) found in a significant fraction of the extremely metal-poor stars in our Galaxy favors a Population III IMF peaked at intermediate mass stars. However, as it has also been shown by previous studies (Gibson & Mould 1997; Fields, Freese & Graft 2000), this inevitably leads to a pollution of the halo ISM at the levels of [C,N/O]> 0.5, which seems rather difficult considering the observed [C,N/O] abundance pattern in Population II halo dwarfs.

Without doubt, further abundance studies in high redshift systems, in particular in Lyman$-\alpha$ forest systems with decreasing hydrogen column density, and in extremely metal-poor stars will soon resolve the question of the existence of Population III and the nature of its mass function.

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Table 2. Evolution in time of IGM metallicity ($Z/Z_\odot$) for the different IMFs.

log t	6.5	7.3	8
Salpeter	$4.2 \cdot 10^{-7}$	$2.1 \cdot 10^{-4}$	$3.1 \cdot 10^{-3}$
YSa	$1.6 \cdot 10^{-7}$	$2.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-2}$
YSb	$1.6 \cdot 10^{-10}$	$4.2 \cdot 10^{-5}$	$2.4 \cdot 10^{-3}$
NUa	$2.2 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$
NUb	$3.2 \cdot 10^{-7}$	$1.6 \cdot 10^{-6}$	$1.7 \cdot 10^{-5}$

Fig. 1.— Comparison of the IMFs used in this work over the range $1 \leq m/M_{\odot} \leq 10^3$. Solid line: Salpeter mass spectrum. Dotted line: YSa. Short dashed line: YSb. Long dashed line: NUa. Dashed-dotted line: NUb.

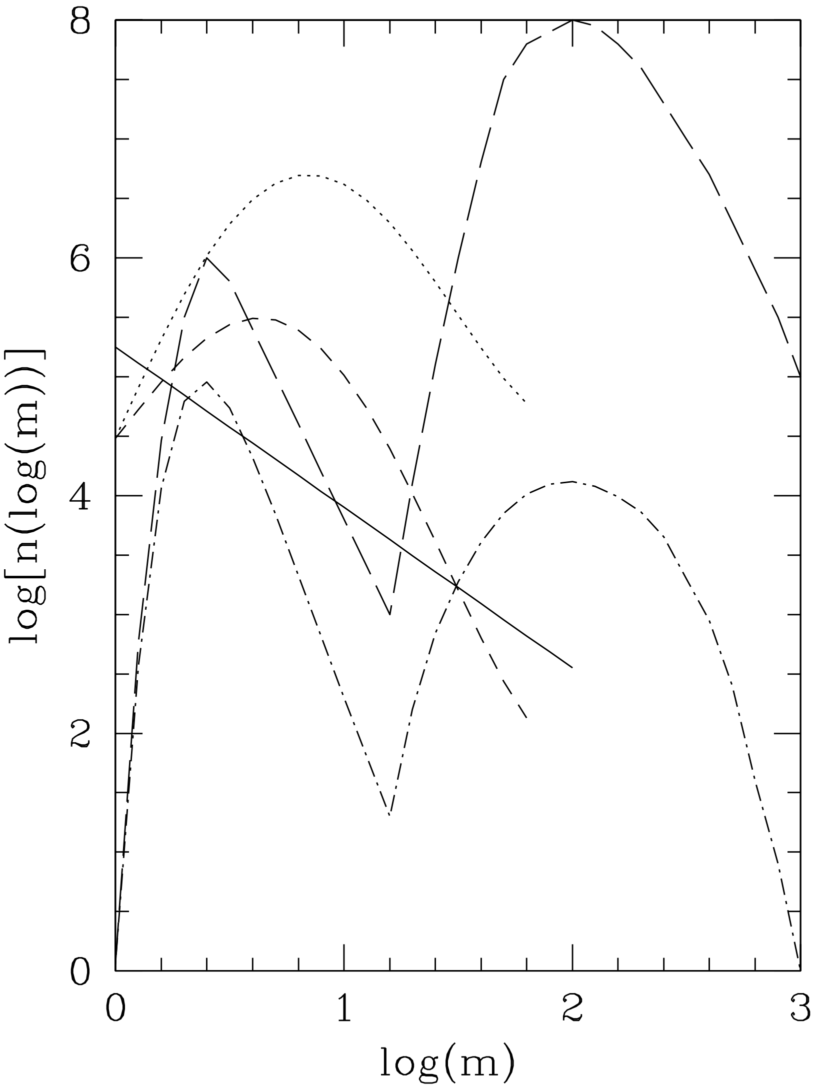
Fig. 2.— Yields (i.e total ejected mass in solar masses) from IMS predicted by van der Hoek & Gronewegen (1997), for $Z = 10^{-3}$ and $\eta = 1$ (solid lines) and $\eta = 4$ (dashed lines), and those computed by Chieffi et al. (2001) for $Z = 0$ and $\eta = 1$ (dotted lines and squares).

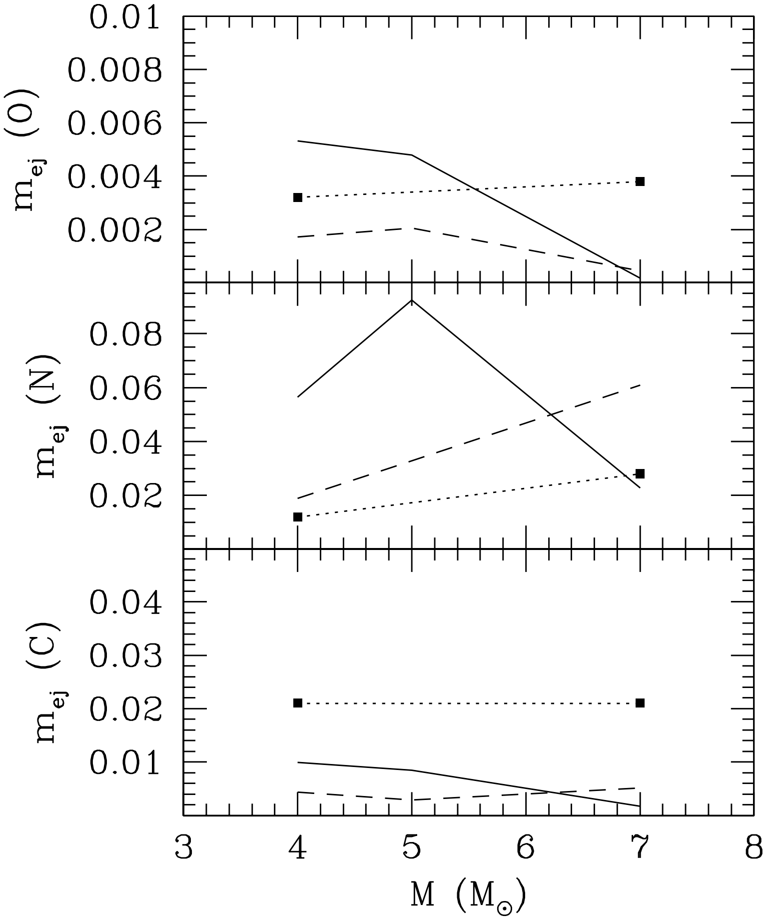
Fig. 3.— Adopted production factors as a function of the stellar mass for certain elements: C (filled squares), N (filled triangles), O (filled circles) and Fe (stars). Note that the oxygen production for a 40 $M_{\odot}$ star is well above the figure limits: $X_O/X_{\odot} \sim 27$.

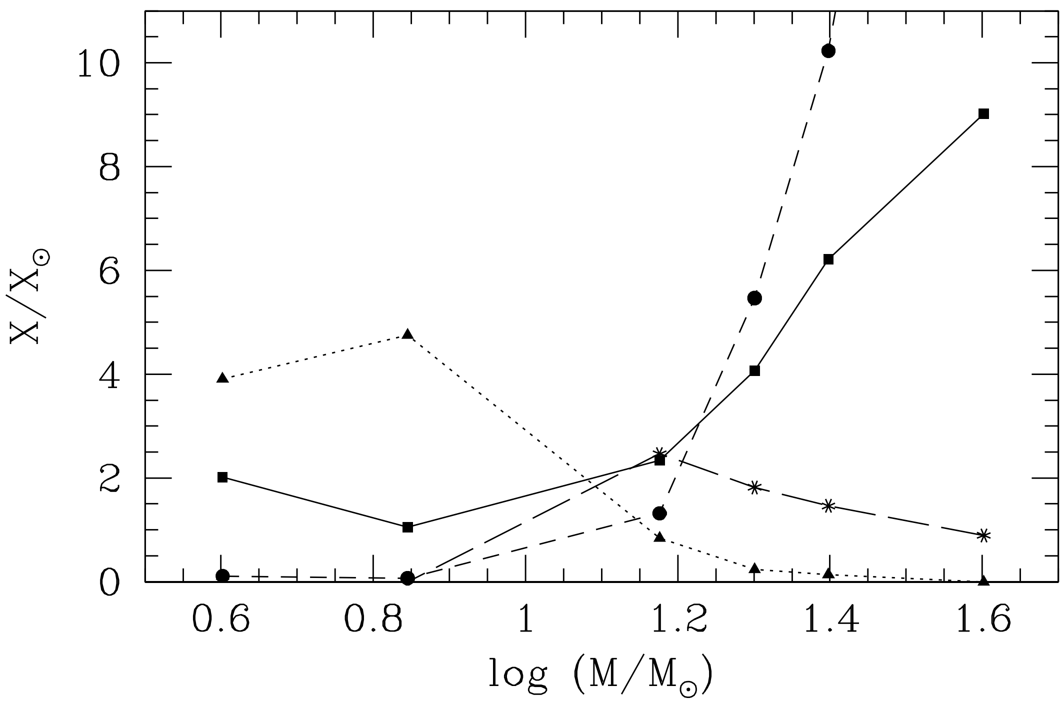
Fig. 4.— Carbon production from Population III stars as a function of the remnant density adopting $\Omega_b = 0.019$ and $H_o = 65$ km/s/Mpc. The various lines represent the results obtained with the IMFs reported in Figure 1. The shaded box define the region in which [C/H]$\lesssim -2.5$ (see §2) and $8 \times 10^{-4} \lesssim \Omega_{sr} \lesssim 10^{-2}$ according to Fields, Freese, & Graff (1998). Key for the curves as in Figure 1. Note that the Salpeter and NUa curves nearly coincide.

Fig. 5.— Evolution of the different abundance ratios in time for the different IMF choices. Key for the curves as in Figure 1.

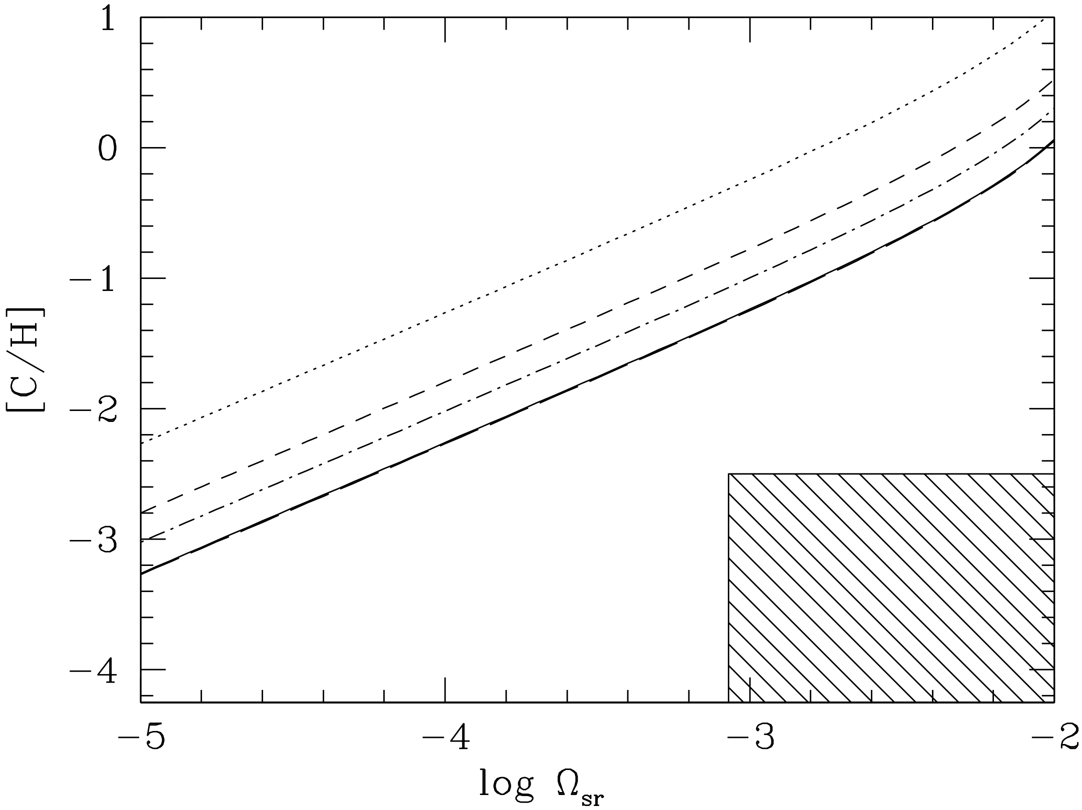
Fig. 6.— Evolution of the IGM [C/O], [C/N] and [N/O] ratios for the model described in §5. Key for the curves as in Figure 1.


8
6
4
2
0
0
1
2
3
log[n(log(m))]
log(m)

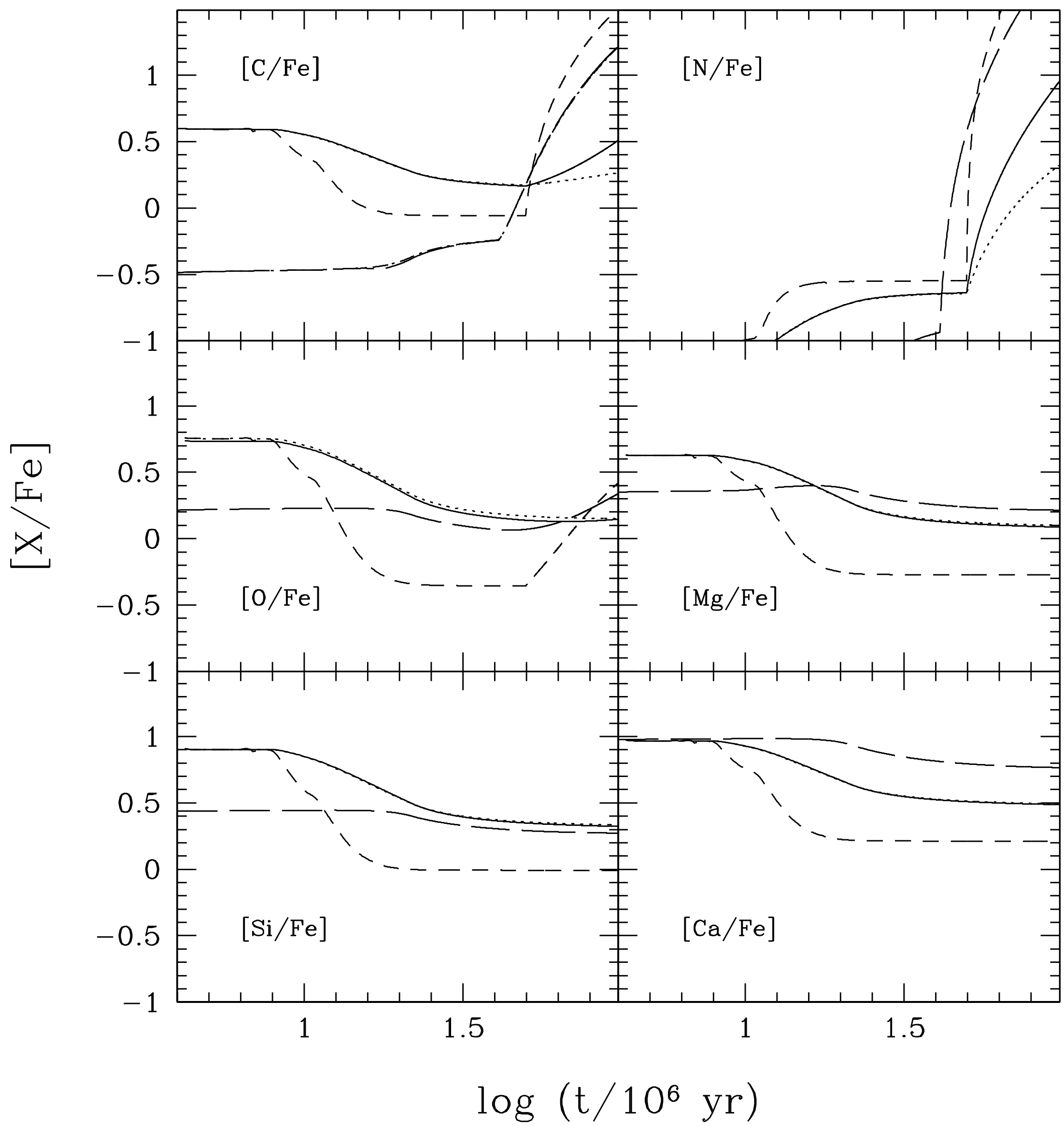

0.01
0.008
0.006
0.004
0.002
m_{ej} (O)
0.08
0.06
0.04
0.02
m_{ej} (N)
0.04
0.03
0.02
0.01
m_{ej} (C)
3
4
5
6
7
8
M ($M_\odot$)



10
8
6
4
2
0
X/X$_\odot$
0.6
0.8
1
1.2
1.4
1.6
log (M/M$_\odot$)



1
0
−1
−2
−3
−4
[C/H]
−5
−4
−3
−2
log Ωsr


[C/Fe]
[N/Fe]
[O/Fe]
[Mg/Fe]
[Si/Fe]
[Ca/Fe]
[X/Fe]
log (t/10⁶ yr)
1
0.5
0
−0.5
−1
1.5

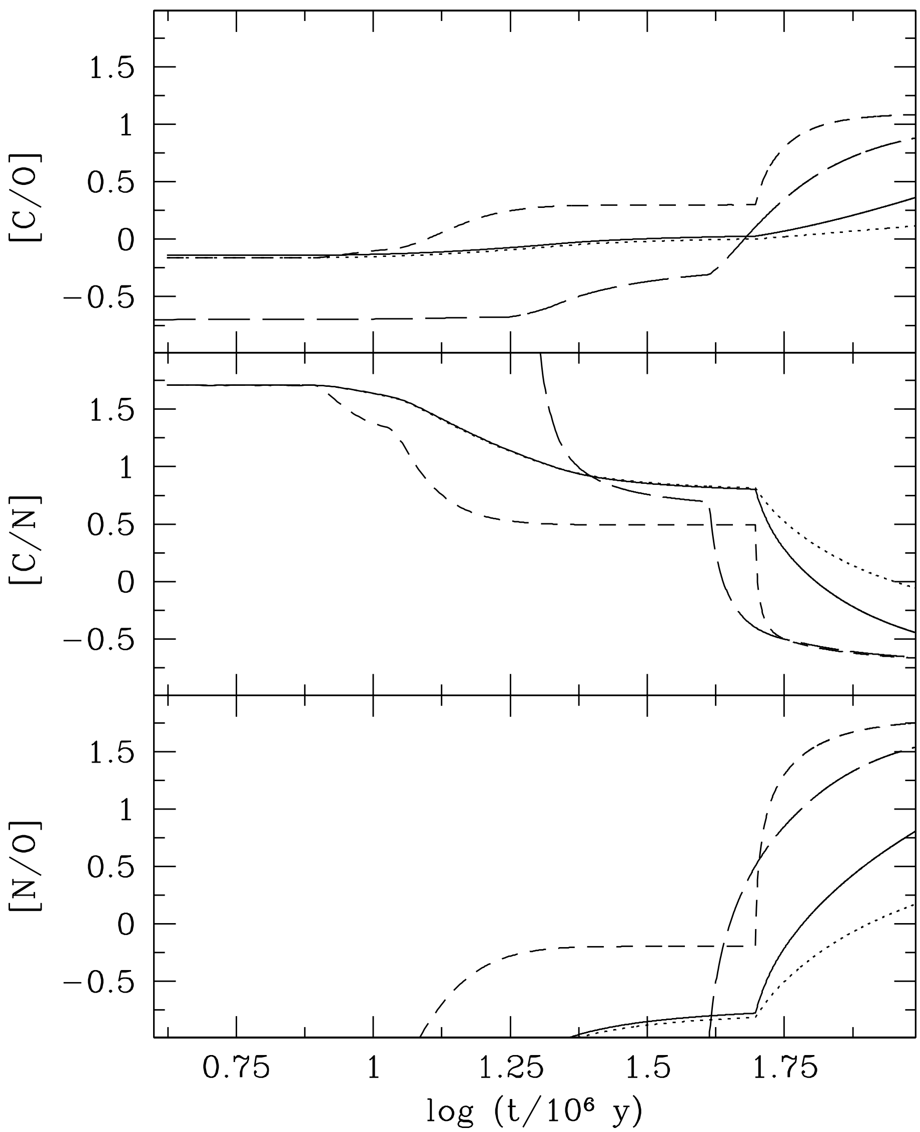

[C/O]
[C/N]
[N/O]
1.5
1
0.5
0
−0.5
0.75
1
1.25
1.5
1.75
log (t/10⁶ y)

Table 1. Results from the starburst model

IMF	$Z/Z_\odot$	p	Ω_{sr}	[C/H]	[N/H]	[O/H]	[Mg/H]	[Si/H]	[Ca/H][a]	[Fe/H]	^{7}Li/H
Salpeter	0.6	$7 \cdot 10^{-3}$	$4 \cdot 10^{-5}$	-2.5	-1.8	-2.5	-3.4	-3.1	-3.3	-3.4	$2 \cdot 10^{-11}$
YSa	1.5	$3 \cdot 10^{-3}$	$8 \cdot 10^{-6}$	-2.3	-2.0	-2.5	-2.6	-2.4	-2.4	-2.7	$4 \cdot 10^{-11}$
YSb	0.45	$9 \cdot 10^{-3}$	$3 \cdot 10^{-5}$	-2.2	-1.6	-3.1	-3.4	-3.0	-3.1	-3.3	$3 \cdot 10^{-11}$
NUa	8	$5 \cdot 10^{-4}$	$1 \cdot 10^{-6}$	-3.2	-3.7	-2.5	-2.3	-2.2	-2.1	-2.2	$7 \cdot 10^{-12}$
NUb	12	$3 \cdot 10^{-4}$	$3 \cdot 10^{-6}$	-3.1	-5.6	-2.4	-2.4	-2.1	-2.0	-2.1	$1 \cdot 10^{-13}$

[a]In the NUa and NUb IMFs the [Ca/H] ratio corresponds to global enrichment in α-elements with $32 \leq A \leq 40$.